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Ballistic variables and tissue devitalisation in penetrating injury—establishing relationship through meta-analysis of a number of pig tests

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Summary

Background: Assessment of the injury potential is central to ascertaining that a law enforcement bullet does not cause unjustified and excessive injuries. There seems to prevail an understanding that tissue devitalisation correlates with kinetic energy dissipated into the tissue. Other views exist too. The purpose of the study was to find out whether such a correlation can be found and at what level of confidence.
Methods: A number of reported tests done with live pigs with sufficient primary data have first been brought to the same temporally comparable level and then analysed. The tests comprise of 140 shots. To maintain consistency tests with other animals were excluded.
Results: The best correlation was obtained between excised muscle tissue and dissipated kinetic energy per millimetre of wound channel. An equation describing the relationship between dissipated energy E_d and devitalised tissue m_{deb} is presented as a regression function $m_{deb} = 44.575 \times E_d + 10.319$ with $R^2 = 0.293$. An experimental method for estimating the energy used for bullet deformation of controlled deformation bullets is also presented.
Conclusions: A method for using the regression function for obtaining tissue destruction figures for any point of wound channel formed in tissue simulant is presented. The figures are intended for meaningful comparison of the injury potential of various bullets and not for forecasting actual tissue injuries. The documentation of the ballistic properties in animal tests also seems somewhat lacking. Some changes in documenting firearms injuries are proposed in order to validate the methods and further enhance the fidelity of simulant testing.

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Nomenclature

E_d	amount of kinetic energy dissipated into tissue
E_{def}	amount of kinetic energy used by deformation of the projectile
E_d/l_w	amount of kinetic energy dissipated into tissue per length of wound channel
E_d/t_{be}	amount of kinetic energy dissipated into tissue per duration of projectile penetration
E_i	kinetic energy of the projectile on impact
E_r	residual kinetic energy of the projectile
l_w	length of wound channel
m_{deb}	amount of debrided tissue
m_{debc}	commensurated amount of debrided tissue
m_{deb}/E_d	amount of debrided tissue per dissipated energy
m_i	impact mass of the projectile
m_{pig}	mass of experimental animal (pig)
m_r	retained mass of the projectile
N	number of observations
S.D.	standard deviation
t_{be}	duration of ballistic event (penetration)
t_{deb}	time delay between shooting and debridement
v_i	impact velocity of the projectile
v_r	retained (residual) velocity of the projectile

Introduction

Several international agreements and recommendations[20–22] require that every weapon must be evaluated to assess its legality before it can enter law enforcement or military use. This calls for a standard method of testing to measure, for example wounding potential of a bullet in various foreseeable circumstances. This is generally done by shooting bullets into blocks of ballistic gelatine simulating muscle tissue although no generally accepted standard for testing and results assessment exists.

One way to assess the level of ballistic injury inflicted to a human being is to measure the amount of tissue, which is surgically removed (debrided, excised) during medical treatment. It has been shown that this amount correlates with the kinetic energy dissipated into tissue by a penetrating bullet.[1,8,12,13,17,23–25] The studies done so far tend to view the dissipated kinetic energy in relation with the length of the wound channel (J/mm). It was therefore interesting to find out whether the mass of debrided tissue correlated better to impact velocity, impact momentum, projectile mass, projectile calibre, dissipated energy per millimetre of wound channel or per millisecond of bullet penetration.

In addition to crushing and perforating the tissue in front of it, a bullet generates a temporary, pulsating cavity, which stretches and compresses the tissue surrounding the wound channel. This is from some aspects comparable to blunt trauma and the injurious effect depends on the amount of compression and the compression velocity and is usually expressed with viscous criterion figure (VC),[2,5] which is their product. Bullets of different velocity can be expected to cause different tissue compression velocities and therefore different injury. It should also be noted that the relationship between the size of temporary cavity and cell death has not been established.[7,11] It has, however, been shown in vitro that cavitation is indeed a prerequisite for cell death as well as major cell damage.[19]

The kinetic energy of a bullet is expended on penetration and cavitation, i.e. dissipated into tissue and consumed by bullet deformation and friction. Friction, however, can be expected to have a negligible effect for practical purposes since only a small area of the bullet touches the tissue. Thus, if bullet deformation did not exist the kinetic energy dissipated into tissue (E_d) would be the difference of impact (E_i) and residual (E_r) kinetic energies.

Defining the energy used by deformation (E_{def}) is difficult. One attempt to overcome this problem is to try to estimate E_d from the fissures formed into gelatine.[10,18] The results are, however, somewhat inconclusive.[16] A bullet may on impact and during penetration deform uncontrollably due to the combination of its structural weakness and instability. Certain bullets have also been designed to deform predictably, consistently and controllably usually by expanding. Both deformation types can be used as bullet design parameters to increase energy dissipation and wounding capacity. Controlled deformation can also be used as a braking mechanism to limit penetration ability and thus danger to non-involved bystanders. Uncontrolled deformation usually means inconsistent performance and to a degree unpredictable results. Since such bullets are neither tactically nor legally desirable the present paper deals with controlled deformation only.

The equation for energy dissipated into tissue can be expressed as:

$$E_d = E_i - E_{def} - E_r \quad (1)$$

Materials

A number of different studies by several authors were selected for meta-analysis using the following selection criteria. The experimental animal must be of the same species to avoid inducing error due to species specific different mechanical properties. The number of reported pig tests is much larger than those with any other animal and therefore pig was chosen. The reports must contain primary data on individual shots. The data must report bullet impact velocity (v_i), impact mass (m_i), dissipated kinetic energy (E_d) and wound channel length (l_w) or sufficient details to calculate the data from.

Albreht et al. (1979)[1]

Forty-two pigs weighing 58—66 kg were used. Individual weights were available. The skin was contaminated with *Escherichia coli* prior to shooting. Both hind legs were penetrated simultaneously. Retrieved bullets were classified as not broken, heavily deformed or fragmented. No detailed data on the retained bullet weights was available. Debridement was done after 6 h. No control group was debrided immediately to see the effect of delayed treatment.

Berlin et al. (1977)[3]

Twenty-seven pigs weighing between 67 and 93 kg were used. Individual weights were not available. Hind legs were shot separately. Retrieved bullets were classified as slightly deformed, deformed and fractured. Possible bone fractures are also noted. Debridement was done within 1 h.

Kjellström et al. (2002)[15]

Sixteen Swedish landrace pigs weighing 42—60 kg were used. One hind leg was shot. The wound was debrided immediately after shooting. The operating surgeon had no knowledge of the brand of ammunition used in each case.

Tikka et al. (1982)[24]

Sixty-four pigs weighing 25—30 kg were used. Individual weights were not available. Both hind legs were penetrated simultaneously. Debridement was done after 6 h. No control group debrided immediately to see the effect of delayed treatment.

Tikka and Seeman (1987)[25]

Twelve Swedish landrace pigs weighing 23—39 kg were used. Individual weights were not available. Both hind legs were shot separately. Debridement was done in 1 h. The results leave some doubt as the exit velocities of the projectiles were not measured but estimated as described by Berlin et al.[4]

A summary of the experiments has been presented in Table 1.

Commensuration of individual results

The experiment results needed to be commensurated to make them comparable before they could be used for analysis.

Bullet deformation and fragmentation use some amount of kinetic energy. Therefore, the difference between projectile kinetic energy on impact (E_i) and on exit (E_r) does not equal to energy dissipated to tissue (E_d). For fragmented and uncontrollably deformed bullets sufficient information was not in all cases available to estimate E_d and E_{def}. The fragmented bullets were therefore excluded from further analysis. Bullet tumbling was not considered a problem. Any bullet instability, unless it causes deformation or fragmentation, only changes the rate of kinetic energy dissipation but does not consume energy. Therefore, $E_{def} = 0$ for non-deformed bullets. The total number of individual shots was 140. Of this number 99 non-deformed and 11 controllably deformed bullets were used for further analysis. All deformed bullets were also used for establishing a regression function for deformation energy E_{def}.

Tikka et al.[24], Tikka and Seeman[25] and Albreht et al.[1] tied the hind legs together and shot simultaneously through both legs. Berlin shot both legs separately. This fact was not considered to introduce any significant error and was ignored.

Delay in wound treatment increases the amount of necrotic tissue. Dahlgren et al.[8] showed that the tissue necrosis is progressive. As the amount of transferred energy varied slightly the amounts of debrided tissue had to be commensurated to filter out the effect of this difference. This was done assuming that the amount of debrided tissue was proportional to the expended energy E_d. This gross assumption can safely be made since the differences in E_d-values were very small. The amount of necrotic tissue increased by about 29% during the first 6 h. After 12 h the increase was 43%. Dahlgren also calculated the amounts of excised tissue per joule of energy. This approach, however, cannot be applied to further commensuration as the process of necrosis is not directly relative to expended energy but to the amount of originally destroyed tissue. According to Bowyer et al.[6] the amount of excised tissue was 100—350 mg during the first hour rising from 100 to 500 mg after 6 h. These figures are, however, far too coarse to allow any conclusions to be drawn. The value of 29% was therefore used to adjust the results of Tikka et al.[24] and Albreht et al.[1]

Table 1 Summary of data used for analysis mean values

Reference	Weapon	Cal	Bullet	m_i	m_{Pig}	N	v_i	E_i	E_d	t_{deb}	l_w	m_{deb}	m_{deb}/E_d
Albreht et al.[1]	Yugoslav M48	7.92 × 57	FMJ	12.85	61.4	4	687.8	3039.5	642.0	6	205.0	123.8	0.19
Albreht et al.[1]	Yugoslav M70	7.62 × 39	FMJ	8	61.7	8	663.2	1759.8	695.6	6	210.0	214.4	0.31
Albreht et al.[1]	Colt M16A1	5.56 × 45	M193[a]										
Albreht et al.[1]	FN FAL	7.62 × 51	NATO FMJBT	9.56	71.2	4	810.5	3139.8	1719.0	6	222.5	527.5	0.31
Berlin et al.[3]	Colt M16A1	5.56 × 45	M193 FMJ	3.6	67–93	3	824.7	1220.3	212.3	1	107.7	103.3	0.49
Berlin et al.[3]	Colt M16 mod 613	5.56 × 45	SS92 FMJ	3.6	67–93	10	855.4	1312.2	287.4	1	106.6	187.5	0.65
Berlin et al.[3]	Husqvarna AK4 (FN FAL)	7.62 × 51	Norma	9.5	67–93	9	731.8	2533.6	293.6	1	118.0	134.1	0.46
Berlin et al.[3]	Valmet M62	7.62 × 39	Russian FMJ	8	67–93	14	631.4	1575.5	292.9	1	127.2	228.3	0.78
Kjellström et al.[15]	Sig Sauer	9 × 19	Norma SP FMJTC	8	52.4	5	368.8	544.5	128.1	1	79.8	24.5	0.19
Kjellström et al.[15]	Sig Sauer	9 × 19	MEN QD[b] MBHP	5.9	50.7	6	401.5	475.6	317.1	1	79.5	42.6	0.13
Kjellström et al.[15]	Sig Sauer	9 × 19	Speer GD[b] JHP	8	48.6	5	355.0	504.2	330.1	1	80.6	49.9	0.15
Tikka et al.[24]	Valmet M62	7.62 × 39	LapuaS309 FMJ	8	20–30	11	663.3	1766.1	142.3	6	95.6	35.2	0.25
Tikka et al.[24]	AKM 47	7.62 × 39	tsDpvth FMJ	8	20–30	13	661.0	1750.4	133.4	6	86.6	21.7	0.16
Tikka et al.[24]	Colt M16A1	5.56 × 45	M193[a] FMJ										
Tikka and Seeman[25]		6 mm	Steel ball	0.86	23–39	18	1078.1	500.6	397.7	1	129.8	112.0	0.28

FMJ, full metal jacket; BT, boat tail; TC, truncated cone; MBHP, monoblock hollow point (expanding); JHP, jacketed hollow point (expanding).

[a] Rejected due to fragmentation.

[b] Controlled deformation bullet.

Table 2 Summary of commensurate mean values used for analysis

References	Cal	Bullet	N	v_r	m_{debc}	m_{debc}/E_d	t_{be}	E_d/t_{be}	m_{debc} correlations			
									E_d/l_w	With E_d	With E_d/t_{be}	With E_d/l_w
Albreht et al.[1]	7.92 × 57	FMJ	4	610.5	87.9	0.14	6.3	100.7	3.1	0.74	0.66	0.67
Albreht et al.[1]	7.62 × 39	FMJ	8	514.2	152.2	0.22	7.1	99.7	3.4	0.25	−0.32	−0.27
Albreht et al.[1]	7.62 × 51	NATO	4	520.5	374.5	0.22	6.9	239.6	7.5	0.05	−0.09	−0.12
Berlin et al.[3]	5.56 × 45	M193	3	747.9	103.3	0.49	2.7	75.6	1.9	1.00	1.00	1.00
Berlin et al.[3]	5.56 × 45	SS92	10	751.4	187.5	0.65	2.7	101.9	2.6	0.61	0.49	0.47
Berlin et al.[3]	7.62 × 51	Norma	9	686.4	134.1	0.46	3.3	88.6	2.5	−0.25	−0.54	−0.53
Berlin et al.[3]	7.62 × 39	Russian	14	555.0	228.3	0.78	4.5	52.4	1.9	0.88	0.85	0.84
Kjellström et al.[15]	9 × 19	Norma SP	5	322.6	24.5	0.19	4.6	27.7	1.6	0.91	0.89	0.86
Kjellström et al.[15]	9 × 19	MEN QD*	6	231.2	42.6	0.13	5.0	63.6	4.0	0.67	−0.05	0.11
Kjellström et al.[15]	9 × 19	Speer GD*	5	208.4	49.9	0.15	5.7	58.6	4.2	0.10	0.10	0.12
Tikka et al.[24]	7.62 × 39	LapuaS309	11	636.0	25.0	0.18	3.0	50.3	1.5	0.18	−0.43	−0.33
Tikka et al.[24]	7.62 × 39	tsDpvth	13	635.3	15.4	0.12	2.7	51.7	1.6	−0.16	−0.63	−0.64
Tikka and Seeman[25]	6 mm	Steel ball	18	485.5	112.0	0.28	3.3	121.5	3.1	0.45	0.38	0.37

* Controlled deformation bullet.

to the 1 h debridement delay level to obtain commensurated mass of debrided tissue (m_{debc}). The average amounts of kinetic energy transferred to tissue (E_d) and the corresponding amounts of debrided tissue (m_{deb} and m_{debc}) are shown in Table 2.

Debridement or excision is to some extent based on the surgeon's subjective assessment.[3] The debridement 4C rule (lack of capillary bleeding, consistency and contractibility and altered colour) used as the basis for subjective assessment is an essential part of the surgical treatment of a bullet wound. The excision may have included tissue, which may have recovered. The variation induced was therefore regarded as an important factor and no attempt was therefore made to exclude it. The results can, therefore, be seen as depending not only on tissue destruction by the bullet but also on the indirect effect of the surgeon's possible under or overestimation of it. The effect of occasional misjudgement is also smoothed by the large number of individual tests. The mean values of m_{debc} and their correlation with E_d is also shown in Table 2. In order to preserve the effect of subjectivity the results showing low m_{debc} to E_d correlation were not excluded.

The bullet velocity was measured at slightly different distances varying up to some 2 m as the bullet velocities were high and the velocity reduction therefore negligible this was not considered as a major source for error and was ignored.

No separation by calibre and bullet type was done because projectile behaviour in tissue depends not only on its kinetic energy but also on its construction. Any generalization on observation of one or two bullet types would be impossible.

Statistical methods

Microsoft Excel 2000 version 9.0.3821 SR-1 was used for statistical analysis. Mean values and standard deviations were calculated. Mean values were compared with two-tailed t-test using 95% level of confidence.

Frequency distributions were formed by grouping the observations of debrided tissue (m_{debc}) into classes according to both energy dissipated per unit length of wound channel (E_d/l_w) and energy dissipated per unit penetration time (ballistic event) (E_d/t_{be}). The latter was considered important in order to see the effect the event speed i.e. projectile velocity has on tissue devitalisation. The class widths were arbitrarily chosen in order to obtain classes having at least four observations. True mean and standard deviation were calculated for each class. The frequency distributions are shown in Tables 3 and 4.

Pearson correlations between m_{deb} and various ballistic variables were calculated and are shown in Table 5.

Regression functions were estimated for all observations included in the analysis using the least square method. The functions were not adjusted to intersect with (0.0) since even in the theoretical case of a bullet not expending any energy into tissue it still crushes a hole (permanent cavity) thereby destroying tissue. Function type was selected by maximising correlation coefficient with the assumption that the curve must be rising. The functions are shown in Figs. 1 and 2.

In order to determine the energy expended on deformation regression functions on m_{debc} per total dissipated energy E_d were estimated for both non-

Table 3 m_{debc} distribution per E_d/t_{be} class

Reference	Cal	Bullet		Class (J/ms)							
				0–35	to 50	to 75	to 100	to 115	to 130	to 190	>190
Albreht et al.[1]	7.92 × 57	FMJ	*N*	0	0	0	2	2	0	0	0
			Mean				48	128			
			S.D.				23	50			
Albreht et al.[1]	7.62 × 39	FMJ	*N*	0	1	0	2	3	1	1	0
			Mean		156		158	166	121	128	
			S.D.				48	10			
Albreht et al.[1]	7.62 × 51	NATO	*N*	0	0	0	0	0	0	1	3
			Mean							170	443
			S.D.								152
Berlin et al.[3]	5.56 × 45	M193	*N*	0	0	2	1	0	0	0	0
			Mean			79	152				
			S.D.			53					
Berlin et al.[3]	5.56 × 45	SS92	*N*	0	0	2	4	2	1	0	1
			Mean			155	106	310	257		264
			S.D.			88	47	78			
Berlin et al.[3]	7.62 × 51	Norma	*N*	0	0	2	6	0	0	0	1
			Mean			217	122				42
			S.D.			101	64				
Berlin et al.[3]	7.62 × 39	Russian	*N*	3	8	1	0	0	0	2	0
			Mean	173	150	30				726	
			S.D.	47	99					185	
Kjellström et al.[15]	9 × 19	Norma SP	*N*	5	0	0	0	0	0	0	0
			Mean	25							
			S.D.	10							
Kjellström et al.[15]	9 × 19	MEN QD[a]	*N*	0	0	5	1	0	0	0	0
			Mean			42	44				
			S.D.			14					
Kjellström et al.[15]	9 × 19	Speer GD[a]	*N*	0	1	4	0	0	0	0	0
			Mean		33	54					
			S.D.			11					
Tikka et al.[24]	7.62 × 39	LapuaS309	*N*	3	2	6	0	0	0	0	0
			Mean	23	67	12					
			S.D.	7	0	3					
Tikka et al.[24]	7.62 × 39	tsDpvth	*N*	2	4	5	2	0	0	0	0
			Mean	18	22	12	10				
			S.D.	0	3	7	1				
Tikka and Seeman[25]	6 mm	Steel ball	*N*	0	0	0	1	7	6	3	1
			Mean				113	114	108	105	140
			S.D.					17	10	10	

[a] Controlled deformation bullet.

deformed and deformed bullets. These functions are shown in Figs. 3.

Results

Tikka et al.[24] used 20–30 kg pigs whereas Albreht et al.[1] and Berlin et al.[3] used 58–93 kg pigs. To find out whether the dissipated energy per unit length of wound channel was different for these two sizes of pigs a number of equivalent test shots had to be chosen. Both Berlin et al. and Tikka et al. had documented the use of calibre 7.62 mm × 39 mm with the same Russian tsDpvth bullet. Berlin et al. shot with Valmet M62 and Tikka et al. with the Russian AKM 47. The fact that different weapons

Table 4 m_{debc} distribution per E_d/l_w class

References	Cal	Bullet		Class (J/ms)						
				0 to 1	to 2	to 3	to 3.5	to 4.5	to 5.6	>5.6
Albreht et al.[1]	7.92 × 57	FMJ	*N*	0	0	1	2	1	0	0
			Mean			64	62	163		
			S.D.				43			
Albreht et al.[1]	7.62 × 39	FMJ	*N*	0	1	1	1	5	0	0
			Mean		156	124	192	149		
			S.D.					24		
Albreht et al.[1]	7.62 × 51	NATO	*N*	0	0	0	0	0	2	2
			Mean						387	362
			S.D.						306	85
Berlin et al.[3]	5.56 × 45	M193	*N*	0	2	1	0	0	0	0
			Mean		79	152				
			S.D.		53					
Berlin et al.[3]	5.56 × 45	SS92	*N*	0	2	6	1	0	1	0
			Mean		155	174	257		264	
			S.D.		88	117				
Berlin et al.[3]	7.62 × 51	Norma	*N*	0	2	6	0	0	0	1
			Mean		217	122				42
			S.D.		101	64				
Berlin et al.[3]	7.62 × 39	Russian	*N*	2	10	0	0	0	1	1
			Mean	147	145				856	595
			S.D.	20	99					
Kjellström et al.[15]	9 × 19	Norma SP	*N*	0	5	0	0	0	0	0
			Mean		25					
			S.D.		10					
Kjellström et al.[15]	9 × 19	MEN QD[a]	*N*	0	0	0	0	5	1	0
			Mean					42	44	
			S.D.					14		
Kjellström et al.[15]	9 × 19	Speer GD[a]	*N*	0	0	0	1	2	2	0
			Mean				33	58	50	
			S.D.					15	10	
Tikka et al.[24]	7.62 × 39	LapuaS309	*N*	2	7	2	0	0	0	0
			Mean	26	29	11				
			S.D.	8	27	0				
Tikka et al.[24]	7.62 × 39	tsDpvth	*N*	1	10	2	0	0	0	0
			Mean	18	16	10				
			S.D.		7	1				
Tikka and Seeman[25]	6 mm	Steel ball	*N*	0	0	7	10	1	0	0
			Mean			113	108	140		
			S.D.			16	10			

[a] Controlled deformation bullet.

were used may introduce some error since the possible differences in barrel length and rifling twist rate may change the bullet's behaviour in tissue. The number of observations for Tikka et al.[24] was 14 and for Berlin et al.[3] 13.

The calculated correlations between mass of debrided tissue (m_{debc}) and total dissipated kinetic energy (E_d) are shown in Table 2. The results of Tikka et al.[24] showed a correlation coefficient of $R^2 = -0.16$ whereas the results of Berlin et al.[3] showed $R^2 = 0.88$. Performing a two-tailed t-test on the mean value of dissipated energy per unit length of wound channel, E_d/l_w gave $t = 0.68$ with critical t-value of 2.13 and $P(T \leq t) = 0.5$. Since the

Table 5 Pearson correlations between debrided tissue and different ballistic variables

Impact velocity (v_i)	0.11
Impact momentum ($m_i \times v_i$)	0.09
Impact kinetic energy ($0.5 \times m_i \times v_i^2$)	0.16
Impact power ($m_i \times v_i^3$)	0.23
Dissipated kinetic energy per mm	0.54
As above but per ms	0.48
As above but per mm/ms	0.06

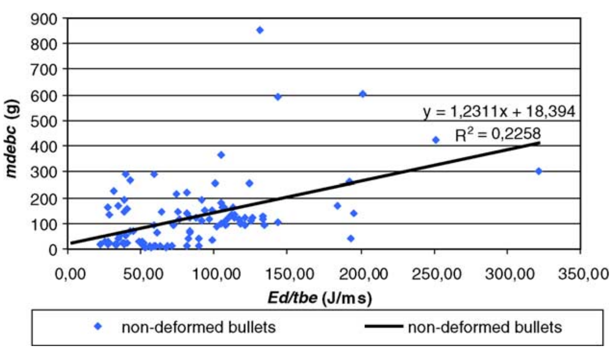

Figure 1 Distribution of debrided tissue (commensurated) by velocity of energy dissipation.

probability of error in accepting or rejecting the hypothesis is 50% it cannot be said that the mean values would definitely be of the same or different distributions. Considering, however, the fact that the correlation of experiments by Tikka et al.[24] is negative ($R^2 = -0.16$) it is safe to deduce that the results obtained with heavier pigs are most likely more reliable.

The best-fit regression function for m_{debc} in grams was estimated as a function of dissipated energy per wound length E_d/l_w in J/mm (Fig. 1) and per velocity of energy dissipation E_d/t_{be} in J/ms (Fig. 2) for all observations of non-deformed bullets. The func-

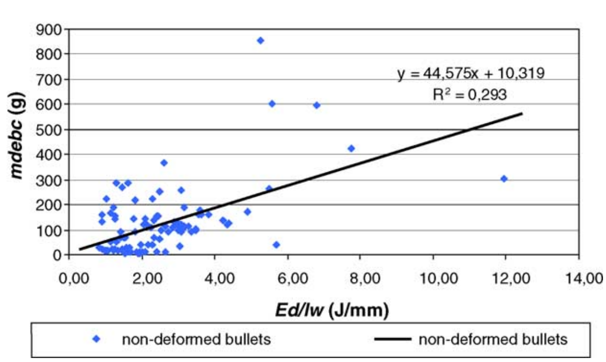

Figure 2 Distribution of debrided tissue (commensurated) by dissipated energy per unit length of wound channel.

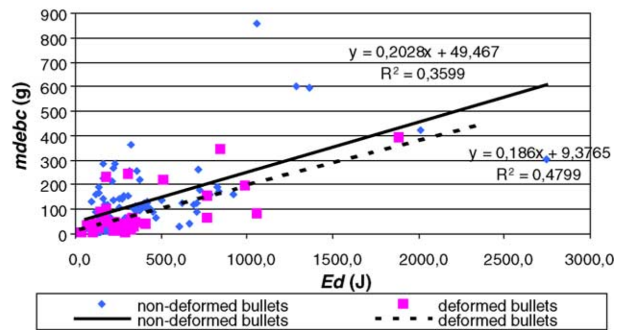

Figure 3 Distribution of debrided tissue (commensurated) by total dissipated energy.

tions and their respective correlation coefficients are:

$$m_{debc} = 44.575x + 10.319$$

with $R^2 = 0.293$ for all observations m_{debc} per E_d/l_w (2a)

$$m_{debc} = 28.455_{e}^{0.0109x}$$

with $R^2 = 0.2426$ for all observations m_{debc} per E_d/t_{be} (2b)

Assessing m_{debc} by E_d/l_w gives higher correlation coefficients than E_d/t_{be}.

The debridement assessment in various experiments differed somewhat. The distribution is shown in Table 1 column m_{debc}/E_d. No definite conclusions can be made on individual assessments because the ammunition selections were not similar and therefore the E_d distributions were different. There are, however, some individual observations that subjectively seem to show far too excessive debridement.

The effect of bullet deformation can be defined as the abscissa difference of the regression functions of deformed (x_{def}) and non-deformed (x_{ndef}) bullets. The m_{debc} distribution per total E_d is shown in Fig. 3 together with linear regressions and their correlations. The function for E_{def} can be defined as:

$$E_{def} = x_{def} - x_{ndef} \qquad (3)$$

Resolving the functions in Fig. 3 with $x = x_{def}$ and x_{ndef} gives

$$x_{def} = \frac{y - 9.3765}{0.186} \qquad (4a)$$

and

$$x_{ndef} = \frac{y - 49.467}{0.2028} \qquad (4b)$$

Substituting x_{def} and x_{ndef} with Eqs. (4a) and (4b) gives

$$E_{def} = \frac{0.0168 \times E_d + 7.29931}{0.038} \qquad (5)$$

In order to verify the correctness of this equation two Gold Dot bullets of the same type Kjellström et al.[15] shot were used. This bullet was measured to produce 392 m/s velocity at 2.5 m from a Heckler & Koch MP5 submachine gun barrel and carry 616 J of kinetic energy[14]. When shooting this bullet into ballistic gelatine it expanded and shortened from an original length of 14.2 mm to an average length of 7 mm. The sample bullets were crushed to this length at the velocity of 3 mm/min using Instron 4505 universal testing machine with 10 kN power cell. The total energy required was 40.46 and 40.57 J, which is assumed to represent the maximum E_{def} for this type when all of its kinetic energy of 616 J is expended in gelatine. The Eq. (5) at the maximum energy gave E_{def} of 464 J, which is far off the 'crush'-measurement value. A theoretical calculation of E_{def} therefore does not seem to produce acceptable results.

Discussion

Unfortunately, the tests analysed are with one exception rather old and the number of shots fired rather low. As such the analysis may be subject to some debate. This was, however, what was available. An attempt to re-examine them provided some interesting information. In some cases it may be inconclusive, but at least it seems to show that more carefully designed research is needed and what type of information should be looked for. Subjective assessment is always a major source for error, but there was no other alternative than to accept the fact. Interestingly, the probability of both over and underestimating the amount of dead tissue seems to grow as the amount of released energy grows. The standard deviations of debrided tissue become higher.

Intuitively, one would expect a deforming bullet to cause more damage. This may be true when the wound channel is observed at a certain depth. Deformation, however, absorbs kinetic energy. When that fact is taken into account the deformed bullet curve in Fig. 3 will probably be very similar to the one of non-deformed bullets. Further analysis would have required knowledge on the degree of deformation of individual bullets and the energies required for deformation. The very limited experiment done with crushing bullets to the same length as they deform to when all their energy has been dissipated into gelatine seems to be a promising way in estimating E_{def}. The method used does, however, not simulate the actual expansion process very faithfully. The pressure in penetration enters the open hollow point cavity expanding its sides outwards. The crushing on the other hand compresses the tip of the bullet axially and inwards. The behaviour of uncontrollably deforming and controllably deforming (expanding) bullets may be different and the crusher-theory may not be applicable to uncontrolled deformation nor to fragmentation.

The rough estimate of E_{def} obtained with crush-test does not take the degree of deformation directly into account. In most cases, a controllably deforming bullet also expands to its maximum deformation level when shot using the velocities relevant to wound ballistic assessment. More work is needed to find a credible method for estimating the kinetic energy used by bullet deformation. The crushing method can be seen as something that is at least available before a better method is found.

There is a slight difference in the regression functions when m_{debc} is correlated to event speed or wound channel length. There are some indications that the tissue devitalisation relationship with energy dissipation velocity is not linear but rather upwards curved when dissipation velocity grows. The number of observations in the high end of spectrum are, however, too few and m_{debc}-values too dispersed to allow any definite conclusions to be drawn. Also, as Fackler comments,[9] the debridement in the pig tests should have been made as blind study to remove any unconscious bias caused by the knowledge of the weapon used. In the work by Kjellström et al.[15] all surgical debridements were performed by the same surgeon, who did not know which type of ammunition had been used in each individual experimental animal.

There prevails a common understanding that fragmentation increases the injury, but no agreement on how much. The test reports mentioned fragmentation, but did not measure its degree, which would have enabled further analysis.

The significance of fissures formed in gelatine has been subject to significant debate.[10,16] Once the regression function for tissue devitalisation and energy used by bullet deformation has been adequately justified, the fissures are needed primarily to establish the point of peak energy dissipation and the relative distribution of kinetic energy along the wound channel in gelatine. As the distribution varies, the m_{debc} values should be estimated separately for every 50 mm section of the wound channel.[18] Calculating m_{debc} for the entire wound channel on the difference of impact and residual energies, E_i and E_r will give incorrect results.

Conclusions and recommendations

It is recommended that a standard regression function (2a) for estimating the mass of devitalised tissue be adopted. This function correlates the amount of devitalised tissue to energy dissipation per wound channel length and gives higher m_{debc} to E_d correlation than function (2b), which correlates devitalised tissue to energy dissipation velocity.

It is further recommended that the energy used for deformation of a bullet of a certain type is established by shooting the bullet into ballistic gelatine with a weapon giving the highest velocity and measuring the residual length. A sufficient number of similar unused bullets are then pressed to the same length measuring the required energy. This number is then used as the maximum E_{def}-value for this bullet type.

The method for obtaining comparison figures for tissue devitalisation caused by non-deforming or controllably deforming non-fragmenting bullets would thus be as follows:

1. Obtain the maximum E_{def} value for the bullet type in question using the crusher-method.
2. Subtract E_{def} from the total energy to obtain energy E_d dissipated into tissue.
3. Estimate the energy dissipation $E_{d'}$ for every 50 mm section of tissue simulant.[10,18]
4. Divide $E_{d'}$ with the section length $l_{w'}$ to obtain $E_d/l_{w'}$.
5. Calculate the mass of devitalised tissue $m_{deb'}$ using Eq. (2a).
6. Sum up all $m_{deb'}$ to obtain total m_{deb}.

It would be necessary to verify the theory described above by collecting accurate information on actual shootings. In addition to describing the injury and treatment any firearm injury documentation should therefore include information on

- weapon used;
- caliber;
- bullet type;
- shooting distance;
- retained weight of the bullet if possible;
- weight of fragments captured and removed from tissue.

References

1. Albreht M, Scepanovic D, Ceramilac A, et al. Experimental soft tissue wounds caused by standard military rifles. Acta Chir Scand 1979;(Suppl. 489):185–98.
2. Assessment Protocol and Biomechanical Limits. European New Car Assessment Programme; (EuroNCAP), Version 3. EuroNCAP Partnership, Brussels, 2001. www.euroncap.com.
3. Berlin RH, Janzon B, Rybeck B, et al. Local effects of assault rifle bullets in live tissues. Part II Further studies in live tissues and relations to some simulant media. Acta Chir Scand 1977;(Suppl. 477):45–8.
4. Berlin RH, Janzon B, Rybeck B, Seeman T. Retardation of spherical missiles in live tissue. Acta Chir Scand Suppl 1979;489:91–100.
5. Bir CA, Viano DC. Biomechanical predictor of *Commotio Cordis* in high-speed chest impact. J Trauma 1999;47(3): 468–73.
6. Bowyer GW, Cooper GJ, Rice P. Small fragment wounds: biophysics and pathophysiology. J Trauma 1996;40(Suppl. 3):S159–64.
7. Coupland RM, Kneubuehl BP, Rowley DI, Bowyer GW. Wound ballistics, surgery and the law of war. Trauma 2000;2(1):1–10.
8. Dahlgren B, Berlin R, Janzon B, et al. The extent of muscle tissue damage following missile trauma one, six and twelve hours after the infliction of trauma, studied by the current method of debridement. Acta Chir Scand 1979;(Suppl. 489):137–44.
9. Fackler M. Letter to the editor on the article: Janzon B, Seeman T. Muscle devitalization in high-energy missile wounds and its dependence on energy transfer (see ref 13). J Trauma 1986;26 (3):297.
10. Fackler ML, Malinowski JA. The wound profile: a visual method for quantifying gunshot wound components. J Trauma 1985;25(6):522–9.
11. Hollerman JJ, Fackler ML, Coldwell DM, Ben-Menachem Y. Gunshot wounds: 1. bullets ballistics and mechanisms of Injury. Am J Roentgenol 1990;155(4):685–90.
12. Janzon B, Hull JB, Ryan JM. Projectile-material interactions: soft tissue and bone. In: Cooper GJ, Dudley HAF, Gann DS, Little RA, Maynard RL, editors. Scientific foundations of trauma. London: Butterworth Heinemann; 1997. p. 37–52.
13. Janzon B, Seeman T. Muscle devitalization in high-energy missile wounds and its dependence on energy transfer. J Trauma 1985;25(2):138–44.
14. Jussila J. Nordic Police Service Ammunition Evaluation 2001. Technical report PTK-TR-A-0002.1; Police Technical Centre, Helsinki 07.11.2001.
15. Kjellström BT, Bursell J, Skoglund M. Sårballistisk utvärdering av polisiär tjänsteammunition; Memo 2002-1625. Stockholm: Totalförsvarets Forskningsinstitut; 2002 [in Swedish].
16. Ragsdale BD, Josselson A. Predicting temporary cavity size from radial fissure measurements in ordnance gelatin. J Trauma 1988;28(Suppl. 1):S5–9.
17. Rong-Xiang F, Yu-Yuan M, Tian-Shun F, Ming L. An estimation of the physical characteristics of wounds inflicted by spherical fragments. J Trauma 1988;28(Suppl. 1):S85–8.
18. Sellier KG, Kneubuehl BP. Wound Ballistics and the Scientific Background. Elsevier; 1994 [ISBN 0-444-81511-2].
19. Sondén A, Svensson B, Roman N, et al. Laser-induced shock wave endothelial cell injury. Lasers Surg Med 2000;26:364–75.
20. The Protocol Additional to the UN Conventions of 12 August, 1949 relating to the Protection of Victims of International Armed Conflicts (Protocol I), 8 June 1977
21. The UN Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons which may be deemed to be

excessively injurious or to have indiscriminate effects. Geneva: The Inhumane Weapons Convention; 1980.
22. The UN Resolution on Small-Calibre Weapon Systems, Geneva; 1979
23. Tian-Shun F, Yu-Yuan M, Rong-Xiang F, Ming L. The wounding characteristics of spherical steel fragments in live tissues. J Trauma 1988;28(Suppl. 1):S37—40.
24. Tikka S, Cederberg A, Levänen J, et al. Local effects of three standard assault rifle projectiles in live tissue. Acta Chir Scand 1982;(Suppl. 508):61—77.
25. Tikka S, Seeman T. Local tissue destruction in high-energy missile trauma and its dependence on energy transfer. Ann Med Milit Fenn 1987;62:17—20.